24510 WOOD DIAPHRAGM MATERIALS 0/4

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## ABSTRACT

Horizontal wood diaphragms, whether used as roofs or floors, are designed to resist such lateral forces as wind and earthquake loads. The primary elements that make up a wood diaphragm are the skin, the framing members, and the connections between the skin and framing members. Materials used as diaphragm skins may be solid or laminated wood decking, plywood, other structural wood-base panels, or some combination of these. Framing members include glulam beams, solid timbers, 2-inch dimension lumber, and various built-up beams and trusses. The skin is attached to the framing members by mechanical fasteners such as nails, staples, or screws or by a combination of mechanical fasteners and construction adhesives.

Each of the materials which go into making up horizontal wood diaphragms is discussed in some detail in this paper, and sources for further information are referenced.

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## INTRODUCTION

As defined in the Timber Construction Manual, [6][3/] structural diaphragms "are relatively thin, usually rectangular, structural elements capable of resisting shear parallel to their edges." Horizontal wood diaphragms, then, are such structural elements made of wood and most commonly used as flat roofs, although floors can also be constructed as diaphragms. Usually only slight design modification is necessary for a conventional frame roof or floor to function as a structural diaphragm.

Structural wood diaphragms may be of heavy-timber construction as used in warehouses and other industrial/commercial buildings, or they may be of light-frame construction as used in residential houses. Heavy-timber construction is discussed by T. G. Williamson [69], and light-frame construction is discussed by Percival and Suddarth [50]. Diaphragms are designed to resist such lateral forces as wind and earthquake loads. The diaphragm skin acts as a web to resist shear stresses while the edge framing members function as flanges to resist bending stresses. The ability of a diaphragm to function effectively as a deep beam is related to the quality of the connections between the skin and the framing members. Thus the three main components of a wood diaphragm are the skin, the framing members, and the connecting system. Except as it applies to two-sided stressed-skin panels discussed later, only the material attached to the top of the framing members is considered in the discussion of diaphragm skin materials.

Skins for wood diaphragms may be made of solid or laminated wood elements, plywood or other structural wood-base panels, or a combination of these. Wood members used as framing include 2-inch dimension lumber, solid wood timbers, glulam beams, built-up plywood beams, and open-web trusses. Other possibilities include built-up beams with hardboard or particleboard shear webs and laminated veneer lumber. Diaphragm skins are connected to the framing by

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1/ Presented at the Applied Technology Council Workshop on Horizontal Wood Diaphragms, November 19-20, 1979, in Los Angeles, sponsored by the National Science Foundation.

2/ Maintained at Madison, Wis., in cooperation with the University of Wisconsin.

3/ Numbers in brackets refer to Literature Cited at the end of this paper.

mechanical fasteners or a combination of mechanical fasteners and adhesives. Nails are the most common mechanical fasteners. Staples and self-tapping screws have also been used. Rigid adhesives are used in the manufacture of glulam beams, laminated veneer lumber, stressed-skin panels, and some open-web wood trusses. Elastomeric adhesives are used in conjunction with nails for onsite joining of skin members and for attaching the skin to the framing members.

The ASCE Committee on Wood has prepared an extensive bibliography on wood and plywood diaphragms [20]. The bibliography is divided into a section on "Current Design Documents" and a section on "Historical and Supplementary Publications." The Committee on Wood has also compiled a state-of-the-art manual on wood engineering for practicing engineers and designers: Wood Structures--A Design Guide and Commentary [13]. This manual is a comprehensive reference source containing recommended basic concepts for engineering use of wood and was used extensively as a resource in preparing this paper. The Commentary provides additional, essential detail on diaphragm materials, their properties, and design considerations that could not be incorporated into this paper. It is recommended supplemental reading.

## TYPES OF WOOD DIAPHRAGMS

(Diaphragm types are illustrated and discussed in more detail by Jephcott and Dewdney in a separate paper included in these Proceedings.)

The Timber Construction Manual [6] lists the following common types of wood diaphragms:

(a) Transverse--Sheathing is either nominal 1-inch boards or nominal 2-inch lumber nailed in a single layer at right angles to the chords using two eightpenny (8d) nails per board per chord crossing.

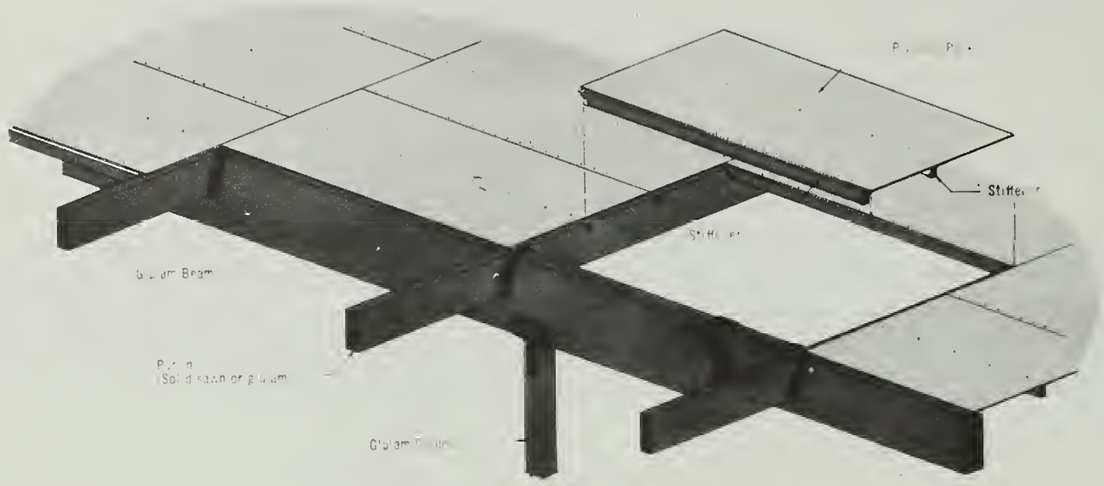
(b) Diagonal--Sheathing is either nominal 1-inch boards or 2-inch dimension lumber nailed at a 45° angle to the chords in a single layer using two or three 8d common nails per board per chord crossing. As many as eight nails are used per board at perimeter members which are designed to resist axial and bending stresses. Diagonal placement of sheathing results in considerably greater strength and stiffness than transverse placement. Diaphragm action of diagonally sheathed wood panels was investigated by Doyle [22].

(c) Double diagonal--Sheathing consists of two layers, one on top of the other, placed 90° to each other. This type of diaphragm is considerably stiffer and stronger than the single-layer types.

Allowable shear stresses for lumber-sheathed diaphragms for various member widths and nailing details are given in the Western Woods Use Book [68].

(d) Plywood--Plywood sheets are fastened to chords, usually by 6d, 8d, or 10d nails, staples, and sometimes by adhesives. For more than 20 years, timber

construction on the West Coast has almost exclusively used plywood sheathing as the diaphragm skin. Detailed information is given in American Plywood Association's (APA) "Plywood Diaphragm Construction" [8]. A very cost-efficient construction method for plywood roof diaphragms is the panelized roof system illustrated below.



The panelized roof system, which involves the use of glulam beams, solid or laminated purlins, and preframed plywood panels, is a construction method used to erect roofs for large industrial and commercial buildings. The following discussion of the materials used in this system was taken directly from Section 10.3.1, pages 314-316, of Reference [13]. It was written by W. H. Bower, M. ASCE, Structural Engineer, Beven-Herron, Inc., La Mirada, Calif., and is used with his permission.4/

Panelized Systems

A variety of panelized roof techniques are used currently to minimize the amount of labor at the roof height. In these techniques, large portions of the roof deck are assembled on the floor before lifting to the roof level. As construction safety requirements become more restrictive, the need for prefabricated roof assemblies becomes more important.

The California panelized roof system is one of the most efficient and successful methods currently available. It is a plywood roof deck on framing that spans 20 to 30 feet between primary beams using purlins usually ranging in size from 4 by 12 to 4 by 18 spaced 8 feet on center (oc). Between the purlins are subpurlins or stiffeners, usually 2 by 4 spaced at 24 inches oc.

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4/ Reference to Uniform Building Code has been revised to conform to 1979 Edition, International Conference of Building Officials, Whittier, California.

Subpurlins may be 2 by 6 where it is necessary to span more than 8 feet at odd cut-in spaces or where the design includes heavy snow loads or unusual dead loads. Occasionally subpurlins are spaced at 16 inches oc, however, this spacing is not efficient.

The significant feature of the California panelized roof system is the orientation of the 4- by 8-foot panel of plywood. The panel is placed with the long dimension parallel to the subpurlin. This arrangement is contrary to the usual practice of spanning plywood with the face grain perpendicular to supports. During the earlier years of use of this system, 3/8-inch-thick plywood was specially manufactured with the direction of face grain parallel to the short dimension of the panel. The cost of this specially manufactured plywood compared to 1/2-inch-thick conventional plywood, together with an increasing need for higher diaphragm strength, eventually caused the 3/8-inch cross-grain plywood to disappear from the marketplace. Calculations of the five-ply, 1/2-inch-thick plywood, utilizing the strength of the second and fourth veneers only, demonstrate that it is adequate for most roof loads with spans typical of the panelized roof. Table 25-R-2 in the 1979 Uniform Building Code, which provides for spans of plywood roof sheathing, permits 1/2-inch-thick, four- or five-ply, Structural I plywood with face grain parallel to supports when continuous over two spans, panel edges are blocked, spacing of supports does not exceed 24 inches, and live load does not exceed 25 pounds per square foot for four-ply and 40 pounds per square foot for five-ply.

(e) Plywood overlaying decking-Relatively thin plywood sheets, 3/8 or 1/2 inch thick, are nailed over random-laid nominal 3- or 4-inch heavy timber decking, either running perpendicular to the decking or at a 45° angle. The plywood provides added diaphragm action in withstanding wind and earthquake loads [36]. The advantage of laying plywood panels diagonally is that plywood joints cannot be alined with decking joints. Alinment of plywood and decking joints, which can occur if plywood is at right angles to the decking, results in a weakened plane in the diaphragm.

## DIAPHRAGM SKIN MATERIALS

### Plywood

#### Construction/Grading Principles

Plywood manufactured under U.S. Product Standard PS 1-74 [62] is widely used in wood diaphragm construction. The primary structural design manual for such plywood is the "Plywood Design Specification" and its supplements [9] published by APA. Baker has compiled a list of technical publications prepared by APA, which contains a section on plywood diaphragm literature [15].

Construction plywood is generally made up of an odd number of layers of veneer at right angles and is referred to as three-ply, five-ply, etc. Plywood

is also constructed with the grain direction of adjacent plies parallel. This construction is often referred to as four-ply, six-ply, etc. Common thicknesses range from 5/16 to 1-1/8 inches. The standard size sheet is 4 by 8 feet, but other sizes can be manufactured. More than 70 species of wood are used in the manufacture of construction plywood. These are assigned to five groups according to similar properties with Group I species being the strongest. Construction plywood may be interior or exterior. Exterior plywood has a fully waterproof glueline. It must also have no lower than C-grade veneer. Interior-grade panels may have any grade of veneers and may be made with exterior, intermediate, or interior glue which is water resistant, but not necessarily waterproof. A typical APA grade-trademark is shown below.

C-D
32/16 APA®
INTERIOR
PS 1-74 000
EXTERIOR GLUE

This panel would have a C-grade veneer face and D-grade veneer back. The identification index, 32/16, refers to a maximum allowable roof support spacing of 32 inches when the panel is used as sheathing and a maximum floor joist spacing of 16 inches when used as subflooring. The panel would be interior type, but would be bonded with exterior glue. Numbers where the "zeros" are shown would identify the mill where the panel was manufactured.

## Design Properties

Allowable plywood design stresses are based on clear wood stresses using the principles in ASTM D-2555, standard methods for establishing clear wood strength values [11]. There are adjustments for such factors as moisture content, duration of load, and veneer characteristics. Duration-of-load factors are the same as those for structural lumber. A table of allowable stresses for plywood is given in the Plywood Design Specification [9] for species Groups 1-4. All species within a group are assigned the same working stress. Design stresses for Group 5 are not assigned. Shown on the following page is an excerpt from that table which includes allowable stresses for bending, tension, compression, shear, and bearing. For stress levels S-1 and S-2, gluelines must be exterior. In addition, only veneer grades N, A, and C are allowed in the face and back for S-1 level. Veneer grades B, C-plugged, and D are allowed on the face or back for S-2 level. "WET" means plywood moisture content in service continuously or repeatedly exceeds 16 percent. When moisture content will be greater than 18 percent, use exterior-type plywood.

Design stresses for the particular plywood grade must be used in conjunction with the section property which applies in the specific case. Section properties in the Plywood Design Specification are given as "effective" section properties. This means they have been adjusted to account for direction of inner plies and possible mixing of veneer species. This subject is covered in more detail in APA's Plywood Design Specification [9] and by Carney in Chapter 5 of reference [13].

### Availability

With all these possibilities, a multitude of plywood grades can be manufactured. However, on a practical basis, only two grades are of concern to the diaphragm designer. One is Structural I C-D plywood made of all Group I species such as Douglas-fir and southern pine. Diaphragms are also constructed using C-D EXT plywood which may have a mixture of species but is bonded with an exterior-grade adhesive.

One-half-inch-thick plywood is used extensively in the panelized roof system discussed earlier. Tongue-and-groove 1-1/8-inch-thick (2-4-1)[5/] plywood nailed to nominal 4-inch beams spaced 48 inches oc is commonly designed for structural diaphragms [1].

### Recent Developments

Composite plywood currently being marketed by two manufacturers in the United States is a new type of structural panel with a structural core of reconstituted wood and veneer faces. Its intended uses include roof sheathing, subflooring, and single-layer floors. The composite plywood panel cannot be interchanged with all-veneer plywood in all applications because all properties are not equivalent. It is felt, however, that for many sheathing and subflooring uses, it is virtually interchangeable with conventional plywood [19]. Composite plywood Sturd-I-Floor panels and roof sheathing panels were used in the construction of a demonstration house in Georgia [38].

## Particleboard

### Classification and Properties

Particleboard is a panel product composed of small pieces--chips, flakes, strands, shavings--of wood bonded together with an adhesive. Particleboard

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5/ Sturd-I-Floor 48oc plywood incorporates all the features of panels formerly designated as 2-4-1.

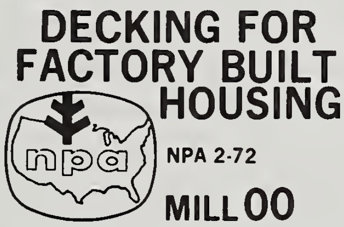
**Table 3. Allowable Stresses for Plywood.**

Conforming to U.S. Product Standard PS-1-74 for Construction and Industrial Plywood. Normal Load Basis in PSI.

| TYPE OF STRESS | | SPECIES GROUP of FACE PLY | GRADE STRESS LEVEL * | | | | |
|---|---|---|---|---|---|---|---|
| | | | *S-1* | | *S-2* | | *S-3* |
| | | | WET | DRY | WET | DRY | DRY ONLY |
| EXTREME FIBER STRESS IN BENDING ($F_b$) | $F_b$ | 1 | 1430 | 2000 | 1190 | 1650 | 1650 |
| TENSION IN PLANE OF PLIES ($F_t$) | & | 2, 3 | 980 | 1400 | 820 | 1200 | 1200 |
| Face Grain Parallel or Perpendicular to Span | $F_t$ | 4 | 940 | 1330 | 780 | 1110 | 1110 |
| (At 45$^o$ to Face Grain Use 1/6 $F_t$) | | | | | | | |

has some of the same uses as plywood in construction, such as sheathing and floor decking, but it is not equivalent to plywood in all properties. Factors that affect particleboard performance include panel density, adhesive content and type, and wood particle size and shape. Panels used in construction are generally sold as 4- by 8-foot sheets, although particleboards are available in larger sizes.

In the particleboard commercial standard, CS 236-66 (now being revised to be reissued as an ANSI standard), panels are classified according to adhesive type, density, and physical property level [60]. Most particleboards are made with urea formaldehyde adhesive and are intended for interior uses such as floor underlayment and corestock for furniture and cabinets. However, some particleboards are made with durable and highly moisture and heat resistant adhesives (generally phenolic resins) for certain exterior applications. The National Particleboard Association (NPA) has standards for panels manufactured specifically for use as single-layer mobile home and factory-built house floor decking [45,46]. Below is one of the NPA grade stamps [44].




NPA 2-72 is the NPA standard for this product. Tongue and groove panels are also manufactured for use as single-layer floors in conventional construction. Building code reports, available from NPA, give allowable shear values for specific brand-name particleboard products when used in horizontal wood diaphragms.

Design values have not been published on an industry-wide basis for structural use of particleboard in the United States. However, work has been done on developing allowable stresses [49]. Such values have been published in Europe. For instance, in Sweden the Svensk Byggnorm contains design stresses for structural grades of particleboard [57].

## Recent Developments

A type of particleboard that has received a lot of attention lately, called waferboard, is made from large, almost square flakes or "wafers" of aspen bonded with the exterior-grade resin adhesive, phenol formaldehyde. It has approval by various code groups for use as exterior sheathing. Currently only one plant in the United States produces waferboard, although several new plants are under construction or announced. Several plants in Canada produce waferboard and ship a large portion to the United States. The total

North American production of waferboard in 1978 was about 600 million square feet (3/8-in. basis). If all the plants under construction or announced actually go into production, the total capacity for waferboard manufacture could be about 2 billion square feet. In comparison, the total U.S. production of construction and industrial plywood is almost 20 billion square feet (3/8-in. basis).

It is possible to mechanically, or electrostatically, aline certain wood particle types to produce panels with increased bending strength and stiffness in one direction. The increase depends upon the degree of alinement. Panels with face flakes, or strands, alined in the direction of the panel length and core flakes alined in the perpendicular direction in a plywood-like construction, have been made and test marketed in the U.S. Construction of a plant to produce such a panel has begun [21].

The U.S. Forest Products Laboratory (FPL), in cooperation with Purdue University, has developed an engineered thick flakeboard roof decking intended for commercial and industrial applications [33]. The panel, a three-layer design, is 1-1/8 inches thick, and has large flakes in the face alined in the long direction of the panel to provide adequate bending strength and stiffness and smaller randomly distributed flakes in the core to resist shear. Purdue University and FPL are currently evaluating the properties of laboratory-made full-size panels 30 inches wide and 12 feet long designed to be continuous over two 6-foot spans.

## Stressed-Skin Panels

Flat stress-skin panels are composites of stringers, usually 2-inch dimension lumber, with plywood skins bonded either to one or both sides. In two-sided panels, which are the most common, the stringers are placed on edge, evenly spaced, between the skins. In one-sided panels, stringers may be used alone or with a flat lumber piece bonded to the bottom of each stringer to form inverted T-flanges. Two-sided stressed-skin panels are designed to act like a series of built-up I-beams, with the skins taking most of the moment stresses as well as performing a sheathing function, while the stringers take the shear stress. The most practical spans for plywood stressed-skin roof panels are 12 to 32 feet. They are also used as floor panels.

Complete design and fabrication recommendations are available from APA [9]. Fastening of stressed-skin panels when a roof or floor is designed as a shear diaphragm may be done in accordance with "Plywood Diaphragm Construction" [8]. The allowable diaphragm load may be limited by the glueline stresses, particularly if one-sided or T-flange panels are used.

In the Federal Republic of Germany (West Germany), particleboard is the panel material used most for the manufacture of stressed-skin panels for one- and two-family houses [53].

## Timber Decking

Timber decking, solid sawn or laminated, must be at least 2 inches in nominal thickness to satisfy code requirements for heavy timber construction. Glued laminated timber decking is manufactured from three or more laminations bonded together into a single member with a tongue-and-groove pattern. It is available in different thicknesses, approximately 2-1/4 to 3-3/4 inches, which may vary between manufacturers. Detailed information on laminated decking is available from the manufacturers and suppliers. Limited stress data is also available from the American Institute of Timber Construction (AITC).

Solid-sawn timber decking may be nominal 2, 3, or 4 inches thick. Nominal width is 6 inches. Nominal 2 by 6 timber decking has a single tongue and groove. Nominal 3 by 6 and 4 by 6 decking has a double tongue and groove. Allowable stress and design information for timber decking is given in AITC 112-77, "Standard for Tongue and Groove Heavy Timber Roof Decking" [2]. Lumber used in heavy timber decking is graded according to the grading rules for the particular wood species used. Lumber grading is discussed in detail below under Structural Lumber.

Nominal 2 by 6 solid-sawn decking, on a laminated beam and purlin system, is toe-nailed at each support with one 16d nail and face-nailed with one 16d nail. Economical span range for 2-inch decking is 6 to 12 feet. Nominal 3 by 6 and 4 by 6 solid timber decking, on a laminated beam system, is toe-nailed at each support with one 40d nail and face-nailed with one 6-inch spike. Adjacent deck boards are also spiked to each other with 8-inch spikes through predrilled edge holes at intervals of no more than 30 inches. Economical spans for heavy timber decking range from 8 to 20 feet, depending upon deck thickness and load conditions [1].

Insurance rating bureaus and all of the model building codes accept 1-1/8-inch tongue-and-groove plywood with exterior glue as an alternative to 2-inch nominal tongue and groove lumber decking in heavy timber construction. Typical construction consists of Sturd-I-Floor 48 oc tongue-and-groove plywood or 1-1/8-inch tongue-and-groove C-D EXT nailed to heavy timber beams which must be 4 by 6 minimum and are normally spaced 48 inches oc [7].

# DIAPHRAGM FRAMING MEMBERS

## Structural Lumber

Besides being used without modification as diaphragm members, solid-sawn structural lumber is used to manufacture glulam beams, timber decking, stressed-skin panels, I-beams and box-beams, and open-web trusses. For this reason, structural lumber is discussed below in considerable detail under visual stress grades and machine stress grades.

## Visual Stress Grades of Lumber

### Grading Principles

The majority of stress-graded lumber used structurally in the United States is graded by a traditional visual grading practice. This procedure was formally instituted through the American Society for Testing and Materials (ASTM) Standards in 1927 [14]. This grading system has been subject to continual review and modification in the years since 1927, principally through ASTM standards procedures, but also under consensus standards promulgated by the U.S. Department of Commerce [59].

The basic premise of the visual stress-grading system is the use of the clear straight-grain wood property as a species characteristic to be further modified by strength-reducing characteristics and design adjustment factors. These are combined to provide an allowable or design property. The clear wood properties are selected by consistent procedures in accordance with ASTM Standard D-2555 "Establishing clearwood strength values" [11]. The properties listed in this standard by species are adjusted by procedures prescribed in the standard for the development of near minimum properties and species group combinations [16,17].

Starting with the clear wood base the next critical step in assignment of design values is to accomodate the natural characteristics of wood. These procedures are outlined in ASTM Standard D-245 "Establishing structural grades and related allowable properties for visually graded lumber" [14]. The basic premise is a factor called the strength ratio. This adjusts the clear wood properties for natural characteristics such as knots and slope of grain. Bending, shear, compression perpendicular and parallel to the grain, and modulus of elasticity properties can be derived directly using D-245. Allowable tension values are determined following D-245 procedures with additional reductions recently applied to accomodate observations from tests of lumber [25]. It is important to recognize that the combined D-2555/D-245 procedures allow derivation of design properties for any species-lumber characteristic combination. This two-standard combination has permitted market flexibility over the years and presently accommodates all of the softwood species and some of the hardwood species considered of commercial importance for structural use in the United States and Canada.

To provide uniformity in the marketplace for lumber sizes, grades, and species combinations, the current American Softwood Lumber Standard (ALS), Product Standard 20-70 [59] was promulgated under the U.S. Department of Commerce in 1970. A feature is the National Grading Rule, a provision of this

standard which was enacted to create particular uniformity in the critical dimension lumber grades.[6/]

Under the ALS, authority is vested in rules-writing agencies to describe the nature and size of characteristics such as knots permitted in all grade/size combinations and to specify permitted manufacturing characteristics such as skip and wane. These agencies also calculate and publish the corresponding design values and have responsibility for inspection procedures. The following agencies are granted rules-writing status under the ALS. Specific inquiries regarding content of grades, grading practices, and allowable properties corresponding to these grades, should be directed to these agencies.

| Organization | Mailing Address |
|---|---|
| Northeastern Lumber Manufacturers Association, Inc. | 4 Fundy Road, Falmouth, Maine 04105 |
| Northern Hardwood and Pine Manufacturers Association, Inc. | Suite 501, Northern Building, Green Bay, Wis. 54301 |
| Redwood Inspection Service | 617 Montgomery Street, San Francisco, Calif. 94111 |
| Southern Pine Inspection Bureau | Box 846, Pensacola, Fla. 32594 |
| West Coast Lumber Inspection Bureau | Box 23145, 6980 Southwest Varnes Road, Portland, Oreg. 97223 |
| Western Wood Products Association | 1500 Yeon Building, Portland, Oreg. 97204 |
| National Lumber Grades Authority (Canada) | 1055 West Hastings Street, Vancouver, B.C. Canada V6E 2H1 |

In addition to agencies vested with the responsibility of preparing grading rules for species, other agencies are certified under the ALS to grade, using the rules prepared by the rules-writing agencies. At the time of preparation of this report, 14 agencies, in addition to the above rules-writing agencies, had grading status for lumber marketed in the United States.

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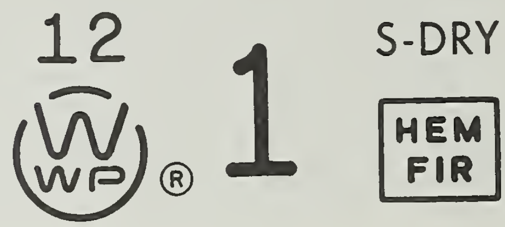
6/ Specifically, the National Grading Rule provides that the same grade description shall accompany all stress grades with common grade names for dimension lumber--the subsequent design values varying in accordance with clearwood properties. Consequently, commonality of grading procedures exist for all lumber 2 to 4 inches thick, graded under the American Lumber Standards procedures.

A typical visual grade stamp is shown below [67]. The stamp shows species group (HEM-FIR), grade (1), dryness at manufacture (S-DRY),[7/] grading agency (Western Wood Products Association), and mill number [11].




The result of the above procedures is a concise grading rule for each grade of lumber, an accompanying list of properties, and a uniform labeling procedure. As an example of a typical grade, No. 2 Douglas Fir 2 by 4 lumber is limited in characteristics that affect strength and stiffness values to provide a fiber stress in bending value of 45 percent of that allowed for clear, straight-grained wood and to provide a recommended design value for modulus of elasticity of 90 percent of that allowed for the clear wood average. This grade is recommended for many construction uses. Characteristics limited include checks, knots, rate of growth, shake, skips, slope of grain, splits, stain, unsoundwood, wane, warp, and white speck. Each limitation is explained in the official grade description [66,67].

## Properties

The procedures outlined above are applied to approximately 45 species or species groups in the domestic United States lumber market. Major species groupings which accommodate the majority of the market are Douglas Fir-Larch, Hem-Fir, Lodgepole Pine-Engelmann Spruce, Southern Pine, and Spruce-Pine-Fir. Other species and species combinations may be equally or more important in certain geographical markets. All are graded, and the properties developed, using the same ALS- and ASTM-based procedures.

Grade names assigned to lumber under ALS standard procedures vary by size, category, and end-use. The following table lists categories and corresponding names pertinent to diaphragm construction. Note that certain names, e.g., Construction, apply only in the narrow widths and thus are not officially used for joist type lumber.

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7/ S-DRY means surfaced at a maximum moisture content of 19 percent. S-GRN, also used, means surfaced at a moisture content above 19 percent (i.e., "green"). Southern Pine Inspection Bureau often uses the "KD" designation to mean kiln-dried to not over 15 percent moisture content.

Grade categories of visually stress-graded lumber used in diaphragm construction

| 2 to 4 Inches Thick* | |
|---|---|
| **2 to 4 Inches Wide** | **5 Inches and Wider** |
| Structural Light Framing | Structural Joist and Plank |
| Select Structural | Select Structural |
| No. 1 | No. 1 |
| No. 2 | No. 2 |
| No. 3 | No. 3 |
| Light Framing | |
| Construction | |
| Standard | |
| Utility | |
| Beams and Stringers - 5 inches and thicker, 8 inches and wider | |
| Decking - several sizes and patterns | |

*All grades described in all United States rules in accordance with the American Lumber Standard. Allowable stresses assigned to Structural Light Framing are not the same as those assigned to Structural Joist and Plank of the same grade name. Allowable stresses also vary with species. All sizes are nominal.

The universal reference for sizes, grades, and species in the United States is the National Design Specification (NDS) supplement labeled "Design Values for Wood Construction" [43]. The excerpt on the following page from the NDS Table 4A illustrates the display of data accompanying one species marketing group (Douglas Fir-Larch) for lumber 2 to 4 inches thick. Additionally, individual rules-writing agencies publish selection guides containing allowable properties for the species/grade/size combinations under their jurisdiction.

## Marketing/Availability

Grades and sizes available in the market vary by geographical region. For example, Southern Pine often is sold as separate grades such as No. 1, No. 1 Dense, No. 2, and No. 2 Dense. The "Dense" connotes an additional growth requirement. It is common to sell western species in combinations such

## TABLE 4A—DESIGN VALUES FOR VISUALLY GRADED STRUCTURAL LUMBER

(Design values listed are for normal loading conditions. See other provisions in the footnotes and in the National Design Specification for adjustments of tabulated values.)

| Species and commercial grade | Size classification | Design values in pounds per square inch: Extreme fiber in bending "$F_b$": Single-member uses | Extreme fiber in bending "$F_b$": Repetitive member uses | Tension parallel to grain "$F_t$" | Horizontal shear "$F_v$" | Compression perpendicular to grain "$F_{c\perp}$" | Compression parallel to grain "$F_c$" | Modulus of elasticity "E" | Grading rules agency |
|---|---|---|---|---|---|---|---|---|---|
| **DOUGLAS FIR-LARCH** (Surfaced dry or surfaced green. Used at 19% max. m.c.) | | | | | | | | | |
| Dense Select Structural | 2" to 4" thick 2" to 4" wide | 2450 | 2800 | 1400 | 95 | 455 | 1850 | 1,900,000 | |
| Select Structural | | 2100 | 2400 | 1200 | 95 | 385 | 1600 | 1,800,000 | |
| Dense No. 1 | | 2050 | 2400 | 1200 | 95 | 455 | 1450 | 1,900,000 | |
| No. 1 | | 1750 | 2050 | 1050 | 95 | 385 | 1250 | 1,800,000 | |
| Dense No. 2 | | 1700 | 1950 | 1000 | 95 | 455 | 1150 | 1,700,000 | |
| No. 2 | | 1450 | 1650 | 850 | 95 | 385 | 1000 | 1,700,000 | |
| No. 3 | | 800 | 925 | 475 | 95 | 385 | 600 | 1,500,000 | |
| Appearance | | 1750 | 2050 | 1050 | 95 | 385 | 1500 | 1,800,000 | |
| [illegible] | | 800 | 925 | 475 | 95 | 385 | 600 | 1,500,000 | |
| | 2" to 4" thick 4" wide | 1050 | 1200 | 625 | 95 | 385 | 1150 | 1,500,000 | WCLIB WWPA |
| | | 600 | 675 | 350 | 95 | 385 | 925 | 1,500,000 | |
| | | 275 | 325 | 175 | 95 | 385 | 600 | 1,500,000 | |
| | | 2100 | 2400 | 1400 | [illegible] | 455 | 1650 | 1,900,000 | (see footnotes 1 through 12) |
| | | 1800 | 2050 | [illegible] | | 385 | 1400 | [illegible] | |
| | | | [illegible] | | | [illegible] | [illegible] | [illegible] | |

as No. 2 and Better (2 & btr), for example. In such a mix there may be grades stamped No. 2, No. 1, and Select Structural.

In dimension sizes the effect of the National Grading Rule is to have the same grade characteristics associated with a common grade name across all species. Therefore the availability of certain stress levels is a function of the clear wood strength. Accordingly, high design values will not be found in some of the dimension grades for species of lower clear wood strength species. For example, a Douglas Fir Select Structural 2 by 4 has an allowable bending strength of 2,100 lb/in$^2$ while the corresponding Select Structural Western Cedar 2 by 4 has an allowable bending strength of 1,300 lb/in$^2$. As a result, users should consider purchasing by desired property level rather than only by species or grade. Such a procedure permits the market to seek the most economical species/grade combination having the proper design value.

In any specific market location, certain combinations of species, grades, and sizes may have greater regional market acceptance, have greater production feasibility, or may be influenced by shipping costs. Consequently, not all possible combinations of size, grade, or species are available in all locations. Specifiers and purchasers concerned with the availability of stress levels, species, or sizes are advised to use the services of the lumber distribution system and particularly sales organizations specializing in industrial lumber in order to minimize confusion regarding the availability of the most optimum combinations of lumber properties.

One possible outcome of the lumber grade assessment is some consolidation of the existing visual grades. Presently the large number of individual species/grade/size combinations causes some marketing concern as being confusing and perhaps inefficient. Careful consideration of the actual structural needs by users--such as in diaphragm construction--would be a positive contribution to the lumber marketing experts as they assess possible changes in market combinations.

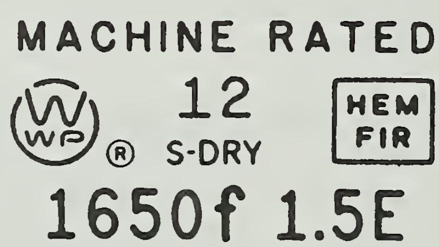
## Machine Stress Grading

### Grading Principles

A second grading system was initiated 15 years ago. This procedure is termed machine stress grading and carries the abbreviation MSR. This system is currently being used in the United States and Canada to a limited degree and is coordinated with the visual grading system. The MSR system is based on measuring the stiffness of each piece of lumber using a mechanical device. This measurement is related to strength through established correlative relationships [31]. The MSR system includes edge-knot and other visual requirements, often termed visual quality levels, as a part of the National Grading Rule requirements [26].

The result is a grading system that is a combination of predicting variables--a stiffness measurement plus the visual criteria. The system functions by adjusting grading machines to adequately measure stiffness from which bending strength is directly inferred based on tests. Allowable tension and compression parallel design values are based on a percentage of the allowable bending value [25,66,67]. Compression perpendicular and shear values are determined as in the visual stress grading procedures [10,17].

An essential element of the MSR system is the certification and quality control requirement that accompanies performance of this system in a production sawmill. A supervisory grading agency uses the certification procedure to establish the grade-size combinations permitted for that individual installation. The grading agency and the production mill utilize an ongoing quality control procedure to verify that the strength and stiffness characteristics of the grade are being met. A grade stamp on Machine Stress Rated lumber indicates that the stress rating system used meets requirements of the grading agency's certification and quality control procedures. MSR lumber is visually graded to limit such characteristics as checks, knots, shake, skip, splits, wane, and warp. Shown below is an example of a grade stamp for MSR lumber [67]. The "f" rating is extreme fiber stress in bending in $lb/in^2$, and the "E" rating is the rated modulus of elasticity in millions of $lb/in^2$.




## Properties

Commercial species groups machine stress graded at this time (1979) are limited primarily to Douglas-fir, Hem-fir, Southern Pine, and Spruce-Pine-Fir. The reasons for this species orientation rests in the yields obtainable, the presently attractive market grades, and the existence of production operations with sufficient sophistication and marketing capability.

Properties for these grades are commonly displayed as shown in the excerpt on the following page from the NDS Table 4B [43, Supplement on Design Values for Wood Construction].

## Marketing/Availability

The MSR grade most prominent at this time is 1.5E-1650f, primarily in support of the metal plate wood truss industry. Other grades available include

## TABLE 4B. DESIGN VALUES FOR MACHINE STRESS RATED STRUCTURAL LUMBER

(Design values listed are for normal loading conditions.[8] See footnotes, and other provisions in the National Design Specification, for adjustments of tabulated values.[10])

| Grade designation | Grading rules agency (see footnotes 1,2,3) | Size classification | Design values in pounds per square inch[5] | | | | |
|---|---|---|---|---|---|---|---|
| | | | Extreme fiber in bending "$F_b$"[9] | | Tension parallel to grain "$F_t$" | Compression parallel to grain "$F_c$" | Modulus of elasticity "E" |
| | | | Single-member uses | Repetitive-member uses | | | |
| 900f-1.0E | 1 | Machine rated lumber 2" thick or less All widths | 900 | 1050 | 350 | 725 | 1,000,000 |
| 1200f-1.2E | 3 | | 1200 | 1400 | 600 | 950 | 1,200,000 |
| 1450f-1.3E | 1 | | 1450 | 1650 | 800 | 1150 | 1,300,000 |
| 1500f-1.4E | 3 | | 1500 | 1750 | 900 | 1200 | 1,400,000 |
| 1650f-1.5E | 3 | | 1650 | 1900 | 1020 | 1320 | 1,500,000 |
| 1800f-1.6E | 3 | | 1800 | 2050 | 1175 | 1450 | 1,600,000 |
| 2100f-1.8E | 3 | | 2100 | 2400 | 1575 | 1700 | 1,800,000 |
| 2400f-2.0E | 3 | | 2400 | 2750 | 1925 | 1925 | 2,000,000 |
| 2700f-2.2E | 3 | | 2700 | 3100 | 2150 | 2150 | 2,200,000 |
| 3000f-2.4E | 2 | | 3000 | 3450 | 2400 | 2400 | 2,400,000 |
| 3300f-2. | 2 | | 3300 | 3800 | 2650 | 2650 | 2,600,000 |
| | 3 | | 900 | 105 | 350 | 725 | 1,000,000 |

...achine Rated Lumber, ... or less, all width...

5. Design values for horizontal shear "$F_v$" (DRY) and compression perpendicular to grain "$F_{c\perp}$" (DRY) are:

| Cedars[7] (WWPA/WCLIB) | Douglas Fir—Larch (WWPA/WCLIB) | Douglas Fir South (WWPA) | Engelmann Spruce (WWPA) | Hem—Fir (WWPA/WCLIB) | Mixed Species (WCLIB) | Pine[6] (WWPA) | Southern Pine (SPIB) | Western Hemlock (WWPA/WCLIB) |
|---|---|---|---|---|---|---|---|---|
| Horizontal shear "$F_v$" (DRY) | | | | | | | | |
| 75 | 95 | 90 | 70 | 75 | 70 | 70 | 90 | 90 |
| | | | | | For Southern Pine KD 95 | | | |
| Compression perpendicular to grain "$F_{c\perp}$" (DRY) | | | | | | | | |
| 265 | 385 | 335 | 195 | 245 | 190 | 190 | 405 | 280 |

6. Pine includes Idaho White Pine, Lodgepole Pine, Ponderosa Pine or Sugar Pine.
7. Cedar includes Incense or Western Red Cedar.
8. Stresses apply at 19 percent maximum moisture content.
9. Tabulated extreme fiber in bending values "$F_b$" are applicable to lumber loaded on edge. When loaded flatwise, these values may be increased by multiplying by the following factors:

| Nominal width (in) | 3" | 4" | 5" | 6" | 8" | 10" | 12" | 14" |
|---|---|---|---|---|---|---|---|---|
| Factor | 1.06 | 1.10 | 1.12 | 1.15 | 1.19 | 1.22 | 1.25 | 1.28 |

10. Footnotes 1, 2, 9, 11 and 19 to Table 4A apply also to Machine Stress Rated Lumber.

1.6E-1800f, 1.8E-2100f, and 2.0E-2400f. The latter two grades have often been sold for proprietary long-span trusses and are of interest also for flat metal plate trusses. The most common size available in these grades is 2 by 4. Two by 3 and 2 by 6, as well as wider widths, are available in smaller quantities.

Potentially any species can be machine graded but the production of specific grades may be emphasized or diminished depending upon characteristics of the species. In 1979 approximately 1 percent of the softwood lumber market, i.e., 300 million board feet, was graded by MSR procedures. Because the quantity of MSR is small relative to visually stress graded material, and because the quantity of specific size-grade combinations may vary by producer and species, MSR lumber should be specified with a clear view of availability and specific need for stress level.

### Trends

The conventional MSR tradition has permitted a variety of grade combinations that have been relatively stable for the last 10 years. Recent rule changes under the ALS have made different E-f combinations possible to better suit the production potential of geographical areas and markets. A few new combinations are now reaching the marketplace.

Increased interest in MSR is evident by both producers and users. There have been recent additions of MSR facilities in both the United States and Canada. Most growth is in production for the engineering areas such as trusses and laminated beams because of the appeal of the certification and quality control procedures as well as desirable combinations of properties. The changes in MSR rules and a better understanding of the sawmill and lumber sales implementation of MSR [26] suggest a future trend of more expansion of this grading system.

## Glued Laminated Timber

### Manufacturing Principles

Structural glued laminated timber, or glulam, is an engineered, stress-rated member made up of three or more wood laminations bonded with adhesives. Glulam has been used in building construction in the United States since 1935. Grain direction of all laminations is approximately parallel to the length of the member, and individual laminations do not exceed 2 inches in thickness. Material, manufacture, and quality control requirements are given in Product Standard PS 56-73, "Structural Glued Laminated Timber" [61]. Glue joint quality is a critical consideration in manufacturing glulam members. Adhesives must comply with the specifications contained in PS 56. Wet-use (waterproof) adhesives may be used for all moisture conditions, but are required when the moisture content exceeds 16 percent for repeated or prolonged periods of time.

Glulam beams are classified as either vertically or horizontally laminated beams according to the orientation of the glueline within the beam cross section. Vertically laminated beams are usually limited in depth to the width of lumber available. Horizontally laminated beams may be 7 feet or more in depth. They are usually limited by the widths of laminating stock available; however, when wide members are needed, the laminations may consist of multiple pieces laid side by side and need not be edge glued if the edge joints are lapped in adjacent laminations. Widths up to 24 inches have been achieved in this manner. Horizontally laminated beams lend themselves to more efficient design because lumber grades can be selectively placed throughout the cross section in accordance with stress requirements [42].

Most glulam timbers are manufactured using visually graded lumber. Research has indicated that stiffer glulam beams of equal or higher strength can be made using machine-stress-rated (MSR) laminations [42]. Supplemental requirements for lumber used in laminating are included in the laminating specifications.

## Design Considerations

Procedures for establishing allowable design stresses for glulam made from visually graded lumber are covered in ASTM D 3737-78 [12]. Discussions are underway in ASTM Subcommittee D 07.02 on Laminated Timber to include "E"-rated lumber in ASTM. Bending proof loaders are becoming available for use by glulam manufactures for testing tension lamination.

Specifications for glulam timbers from these and other species used are available from the American Institute of Timber Construction which is the national technical trade association for the glulam industry [3,4,5]. An overall discussion of glulam design and applications is given in the AITC publication "Glulam Systems" [1]. More complete design information is given in the _Timber Construction Manual_ [6]. An example of allowable unit stresses for glulam is shown in the excerpt on the following page from Table 2.9 of the _Timber Construction Manual_. Part B of Table 2.9 gives allowable stresses for wet-use conditions. Allowable stresses published in the United States for glulam bending members are applicable to members 12 inches or less in thickness. When the depth of a rectangular beam exceeds 12 inches, the allowable unit stress in bending ($F_b$) must be reduced by using a size factor discussed in Chapter 2 of the _Timber Construction Manual_. Method of loading and span-depth ratio are also design considerations in adjusting bending stresses.

TABLE 2.9

ALLOWABLE UNIT STRESSES (psi) FOR STRUCTURAL GLUED LAMINATED TIMBER FOR NORMAL CONDITIONS OF LOADING, MEMBERS STRESSED PRINCIPALLY IN BENDING, LOADED PERPENDICULAR TO THE WIDE FACE OF THE LAMINATIONS[a,b,c]

*Part A* Dry Condition of Use

| Combination Symbol | Number of Laminations | Allowable Unit Stresses | | | | | | Modulus of Elasticity $E$ |
|---|---|---|---|---|---|---|---|---|
| | | Extreme Fiber In Bending $F_b$ | Tension Parallel to Grain $F_t$ | Compression Parallel To Grain $F_c$ | Compression ⊥ to Grain: Tension Face $F_{c\perp}$ | Compression ⊥ to Grain: Compression Face $F_{c\perp}$ | Horizontal Shear $F_v$ | |
| **Douglas fir and larch** | | | | | | | | |
| 16*F* | 4 or more | 1,600 | 1,600 | 1,500 | 385 | 385 | 165 | 1,600,000 |
| 18*F* | 4 or more | 1,800 | 1,600 | 1,500 | 385 | 385 | 165 | 1,700,000 |
| 20*F* | 4–8[e] | 2,000 | 1,600 | 1,500 | 410 | 410 | 165 | 1,700,000 |
| | 9–12[d] | 2,000 | 1,600 | 1,500 | 450 | 450 | 165 | 1,700,000 |
| | 13 or more | 2,000 | 1,600 | 1,500 | 385 | 385 | 165 | 1,700,000 |
| 22*F* | 4–10[e] | 2,200 | 1,600 | 1,500 | 410 | 410 | 165 | 1,800,000 |
| | 4 or more | 2,200 | 1,600 | 1,500 | | 385 | 165 | ' 800,000 |
| 24*F* | 4 or more | | 1,600 | 1,500 | | 385 | | |

*Note:* [illegible]

A quality control and inspection system for glulam is provided by AITC based on PS 56 and the AITC Inspection Manual. Below is an example of a custom product quality inspection mark [1]. Each qualified plant has an individual designation. The designation "P-143," shown below, is used for illustration only and is not assigned to any plant.


Marketing

Two of the principal species used for laminations are Douglas-fir and southern pine although the AITC specifications cover a number of other softwood species and hardwoods [3,4,5]. Glulam beams and girders that can span 100 feet or more are key factors in the plywood panelized roof system. The glulam main beams support solid-sawn or glulam purlins which in turn support the preformed plywood panels. Glulam spans considered most economical for the panelized roof system range from 30 to 80 feet. Longer or shorter spans are also possible depending on the particular design situation [1].

## Laminated-Veneer Lumber

Parallel-laminated-veneer lumber (LVL), as the name implies, is made by laminating veneers together with all plies parallel to make 2-inch dimension lumber or larger structural members. Interest in laminating veneers was generated by the need for high-strength lumber from lower quality raw material. Research on laminating veneer ranging from 0.1 to 0.5 inch thick indicates that a product more homogeneous than conventional lumber is possible [41]. Lumber produced from laminating veneers allows randomization of defects, which results in a higher-quality, more uniform product. LVL has been produced with veneer 0.10 to 0.25 inch thick [37,70]. One manufacturer uses C- and D-grade veneers laminated with a phenolic resin adhesive. The continuous "billet," 24 inches wide and up to 2-1/2 inches thick, emerges from the press and is cut to lengths up to 80 feet and to desired widths. A major use for this material is for top and bottom flanges of plywood-web I-beams and open-web wood-steel trusses [48]

FPL has investigated a process for quickly producing structural members from parallel-laminated veneers, using rotary cut veneers up to 1/2 inch thick [64]. Producers can go from log to ready-to-use product in less than an hour. In this process, called Press-Lam, logs are first peeled on a lathe

into veneer. This veneer is then clipped into sheets and press dried in a rapid new process producing a flatter and more stable product than that obtained through conventional drying. These veneer sheets are coated with adhesive while still hot and then laminated in an overlapping fashion so that the butt joints in the different layers do not occur close to one another. A wide, thick panel of continuous length can be built up from these sheets. After pressing, where residual heat from drying helps cure the adhesive, the resultant panel can then be cross cut and ripped into timbers of desired dimension.

As a demonstration project, a 6- by 12-inch Press-Lam beam, 47 feet long, was installed as the basement beam for a factory-built house [71]. Other potential markets for Press-Lam include truss chords, tension laminations for glulam beams, and roof deck support systems.

## Composite Lumber

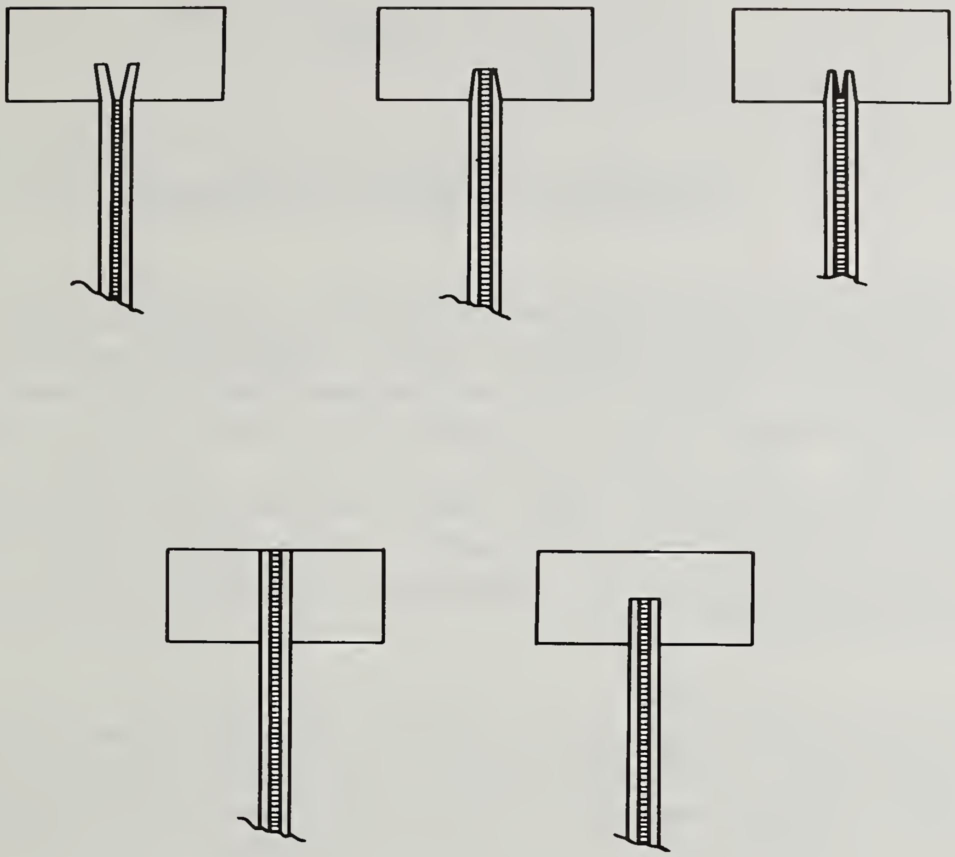
The Southeastern Forest Experiment Station of the Forest Service, USDA, in cooperation with HUD and with assistance from forest products manufacturers, has developed a composite veneer-particleboard floor joist for light-frame construction [23]. It is a structural sandwich construction with a particleboard core bonded between layers of parallel-laminated veneers. The particleboard core makes up 70 to 80 percent of the composite. Although not commercially available, 2 by 8 and 2 by 10 members designed to be used interchangeably with conventional floor joists in house construction were used, 24 inches on center, in the construction of a demonstration house [38].

## I-Beams and Box-Beams

Glued plywood beams are generally fabricated with solid or LVL lumber flanges and Structural I or C-D EXT, plywood webs. Webs are commonly 3/8- or 5/8-inch plywood. The construction may be either I- or box-beam design, but the I-beam configuration is most popular. Design procedures for plywood beams are available from APA [9].

Prefabricated glued plywood I-beams with the plywood web face grain oriented vertically are available from different manufacturers who also supply load tables for different beam sizes and technical assistance in selection and use. Manufacturers' literature lists beams available in depths up to 24 inches and in lengths up to 80 feet. Some of the various configurations for the

flange-to-web joint are shown below. Within certain size and spacing limitations as specified in the manufacturers' literature, holes can be cut in the plywood web for installation of ductwork, plumbing, and wiring.



Because of the availability of the material, hardboard has been used in Europe as the shear web in built-up wood beams. Hardboard-web I-beams were used in Sweden more than 40 years ago [39]. Twelve-meter-long hardboard-web I-beams were installed in a building recently constructed in London [24]. FPL has published several technical reports on the use of hardboard in I-beams [51,55,56] and has developed background information necessary for assigning design stresses to hardboard [40]. However, there are currently no published design values in the U.S. for hardboard. Structural particleboard has also been proposed as a shear web material [32].

## Open-Web Trusses

Open-web trusses are available that have wood flanges and either wood or steel web members. One all-wood truss design has finger-joint connections between web and flange members. Another design uses metal truss plate connectors. One wood-steel truss design uses steel tubes as web members and 2-inch dimension lumber, either solid sawn or laminated veneer, as flange members. Steel pin connections are used between web and flange members. Parallel chord trusses with double 2 by 6 flange members may be up to 63 inches

deep and designed to span close to 80 feet. These are proprietary products which have specific regulatory approvals.

Custom designs for specified loads and dimensions are usually provided by the manufacturer [47]. Technical assistance is also available for proper sizing and selection of truss design. The open-web design can easily accommodate ductwork, plumbing, and wiring.

## INFLUENCE OF END-USE ENVIRONMENT

Design properties for diaphragm elements as generally published are based on normal (10 year) loading assumptions and a moderate temperature moisture content environment. Where the end use varies from these conditions, e.g., high temperature or high moisture contents, the NDS provides advice on property modifications [43]. Some end uses may anticipate a load duration other than conventional 10-year loading. Also, many designs must be checked for adherance to several loading conditions, i.e., snow, wind, earthquake, etc. NDS provides both a load-duration curve and a commentary to assist in carrying out this analysis [43, Appendix B].

In addition to NDS, other wood design references are available to assist in application and modification of published design values to specific end uses [29,30,54,63,68]. It is important to note that some wood products such as particleboard, glulam, and LVL originate by manufacturing processes that result in design property/end-use relationships different from lumber. Consequently, end-use property adjustments for some of these products may vary from those of solid wood. The design advice of the appropriate industrial association should be sought.

For applications involving chemicals, or combinations of severe environmental conditions, such as high temperature and moisture, caution is recommended. General principles of wood performance under these conditions are outlined in the Wood Handbook [63]; however, current industrial experience is often a necessary input to such design applications. Where decay and fire are hazards, specification of appropriate pressure-impregnation treatment should be considered.

## CONNECTING SKINS TO FRAMING MEMBERS

Strength and stiffness of wood diaphragms depend primarily on the fasteners used to connect the skin to the framing members. The connections may be mechanical fasteners or adhesives or a combination of both. Adhesives provide stress transfer from the skin to the framing members with the load distributed over the entire bonded area. Forces are transferred from surface to surface. In contrast, mechanical fasteners, such as nails, develop localized load transfer from within the thickness of the skin and framing members. The

use of both adhesives and mechanical fasteners combine the advantages of both systems, but in many applications this is not economical [13].

## Mechanical Fasteners

(This section has purposely been kept brief since the performance of mechanical fasteners in wood diaphragms is presented in detail by E. G. Stern in a separate paper included in these proceedings.)

Nails are the mechanical fasteners used most often in wood diaphragm construction. There are many types, sizes, and forms of nails. The most frequently used nail is the bright, smooth, common steel wire nail which is available in sizes from four- to sixtypenny. Six-, eight-, and tenpenny (6d, 8d, and 10d) common nails are used extensively in wood diaphragm construction.

Application instructions for heavy timber decking refer to spikes, which are nothing more than large nails. Common wire spikes come in lengths from 3 to 12 inches. They are larger in diameter than common wire nails of the same length, and beyond the 60d size they are usually designated by inches of length.

Various deformed-shank nails such as annularly threaded and helically threaded nails can provide higher withdrawal resistance than plain-shank nails of the same size. Deformed-shank nails are recommended for certain floor constructions such as the APA Sturd-I-Floor.

Staples have been tested as fasteners in diaphragm construction [58] and are accepted for attaching roof sheathing and subflooring. Typical staple size for these uses are 14- or 16-gage galvanized steel wire. Because of the reduced diameter of staple legs as compared to nail shank diameter, staples are spaced closer together than nails.

Manual No. 19-71, "Pneumatic and Mechanically Driven Building Construction Fasteners" [34] contains descriptions, installation details, and spacings for staples, T-nails, modified and conventional roundhead nails, and deformed-shank nails used with pneumatic or mechanical nailers. The tables of allowable shear values are separated into two groupings, one for diaphragm and one for non-diaphragm construction. A footnote to Table III on plywood diaphragms states that plywood not exceeding 1-1/8 inches in thickness may be connected with T-nails, roundhead nails, modified roundhead nails or staples provided the fastener penetration into the main member meets the specified requirements. Manual No. 19-71 is included in its entirety as an integral part of FHA's "Application and Fastening Schedule: Power-Driven, Mechanically-Driven, and Manually-Driven Fasteners" [65].

Self-drilling, self-tapping screws have also been used to attach plywood diaphragm skins directly to all-steel open-web joists [58].

## Adhesives

Adhesives used in diaphragm construction include both rigid and elastomeric. The use of rigid adhesives is limited to factory-type operations because they require carefully controlled conditions which are not typical of onsite construction. Rigid adhesives are used in the manufacture of such diaphragm components as plywood, glulam, laminated-timber decking, built-up plywood beams, laminated-veneer lumber, and stressed-skin panels.

Until synthetic resin adhesives were introduced in the 1930's casein was the dominant structural adhesive for wood where greater water resistance was required than could be provided by animal and vegetable adhesives. It is still extensively used in structural components intended for interior application [18].

For the most durable joints subjected to severe conditions, such as direct exposure to the weather, the adhesives of choice are the phenol and resorcinol resins or blends of the two. Phenolic-resin adhesives are widely used to produce construction plywood by hot pressing to yield exterior-type gluelines. Resorcinol and phenol-resorcinol-resin adhesives can be cold pressed and find use for gluing laminated timbers that will withstand exposure to the weather [27]. Details on composition, properties, and durability of rigid and elastomeric adhesives can be found in Adhesives in Building Construction [28].

Onsite or field gluing became practical, even under adverse conditions, with the introduction of elastomeric adhesives in the 1960's. In diaphragm construction, elastomeric adhesives are used together with nails to connect the skin to the framing members. In the APA Glued Floor System, the adhesive is applied in the joint between plywood panels and to the top edge of the joists before each panel is fastened down. By gluing the plywood to the joists, nail popping and squeaking floors are practically eliminated. The added stiffness as a result of composite T-beam action permits wider spacing of joists or longer spans for some joist sizes. In some floors, joist sizes may be reduced. Also fewer nails are required [52]. Construction adhesives for field gluing plywood to wood framing must meet minimum performance standards specified in ASTM D-3498 [10].

Application of elastomeric adhesives to the tongue-and-groove joints between solid or laminated-timber decking can greatly increase the strength and stiffness of roof diaphragms [35,72].

Elastomeric adhesives are ready-mixed and can be applied with hand caulking guns. They are also available in large containers for use with portable pneumatic systems. For reliable performance, elastomeric adhesives must have adequate shear strength, they should form reliable bonds under a wide range of temperature and moisture conditions, and they need good gap-filling qualities to bond members within ordinary tolerances of fit typical of onsite construction. The adhesive should also maintain adequate strength after exposure to wetting and drying and should not become brittle or deteriorate with age [52].

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